## *OPTICAL TORQUE.*[1]

### I.

SEVENTY-EIGHT years have elapsed since the first discovery, by Arago, of the remarkable chromatic effects produced by slices of quartz crystals upon light, previously polarized, which was caused to traverse them. These effects were shown, one year later, by Biot, to be caused by a peculiar action of the quartz in rotating the plane of polarization; the amount of the rotation being different for lights of different colours. Ever since then, the rotation of the plane of polarization of light has been a topic familiar to physicists. It has stimulated the devotee of research to an endless variety of experiments and suggestive speculations: it has lured on the mathematician to problems which tax his utmost skill: it has afforded to the lecturer an array of beautiful and striking illustrations. Here, in this place, made classical by the researches and expositions of Thomas Young, of Michael Faraday, and of William Spottiswoode, and last, but not least, by the labours of those eminent men whom we rejoice still to number amongst the living—here, I say, on this classic ground, the rotation of the plane of polarization of light is almost a household word, and its phenomena are amongst the most familiar. We know now that not only certain actual crystals, such as quartz, bromate of soda, and cinnabar, rotate the plane of polarization, but that many non-crystalline bodies—liquids, such as turpentine, oil of lemons, solutions of sugar and of various alkaloids, and even certain vapours, such as that of camphor—possess the same property.

In 1845, at the very culminating point of his unique career of research, Faraday opened a new field of inquiry, linking together for the first time the science of optics with that of magnetism, by his discovery that the rotation of the plane of polarization of light could be effected by the application of magnetic forces. This effect he observed first in his peculiar "heavy-glass," when it lay in a powerful magnetic field. Subsequently he found other bodies to possess similar properties: some of these being magnetic liquids, such as solutions of iron, others being diamagnetic. Time will only permit me in passing to refer to the researches of Verdet, and those of Lord Rayleigh and of Mr. Gordon upon the numerical values of the magneto-optic rotation in these substances. H. Becquerel has extended them to gases, and has shown how the magnetism of the earth rotates the plane of polarization of the light which, previously polarized by reflection from the aërial particles which give the sky its "blue," passes earthward through the oxygen of the air.

Other experimenters have dealt with the rotatory effects (whether crystalline, molecular, or magnetic) in relation to lights of different colours, and have studied the dispersion which arises from the greater actual angle of optical torsion which is produced upon waves of short wave-length (violet and blue) than that which is produced under the influence of equal rotatory forces upon the waves of longer wave-length (red and orange). It has also been demonstrated that the plane of polarization of waves of invisible light, whether those of the infra-red, or those of the ultra-violet species, if they have been previously polarized, can be rotated just as can that of waves of visible light.

In 1877, Dr. Kerr, of Glasgow, discovered a point which Faraday had sought for, but fruitlessly—namely, that in the act of reflection at the pole or surface of a magnet, there is a rotation of the plane of polarization of light. This discovery was completed in 1884 by Kundt, of Strasburg, by the further demonstration, also dimly foreseen by Faraday, that a magneto-optic rotation of the plane of polarization is caused by the passage of previously polarized light through a normally magnetized film of iron so thin as to be transparent.

Lastly, in this brief enumeration, we were shown a month ago, by Oliver Lodge, how the magnetic impulses generated by the rapid oscillatory discharges of the Leyden jar can produce corresponding rapid oscillatory rotation in the plane of polarization of the waves of previously polarized light.

You will not have failed to notice the cumbrous phrase which, whether in speaking of the purely optical effects (of quartz, or sugar, or turpentine), or in speaking of the magneto-optic effects of more recent discovery, I have employed to connote a very simple fact. You may have wondered that any lover of simple English speech should indulge in such sesquipedalian words.

Of course, at this period of the nineteenth century it is no longer open to debate that light consists of waves. The plane of polarization of the waves of light is the plane of polarization of the light itself. The rotation of the plane of polarization is the rotation of the polarized waves, and therefore of the polarized light itself. Yet I must draw attention to the fact that in all the array of discoveries which I have enumerated, that which had been observed was the rotation—whether by crystalline, molecular, or magnetic means—not of natural light, but of light which had by some means been previously polarized. It was not known to Arago or to Biot, to Fresnel, to Faraday, nor even to Spottiswoode or to Maxwell, that natural unpolarized light could be rotated. They may have inferred so, but it was not in their time even demonstrable that a beam of circularly-polarized light could be rotated upon itself in the same sense as that in which a beam of plane-polarized light could be rotated.

That light of any and every kind, however polarized or devoid of that which is called polarization, can be, and in fact is, rotated when it passes across a slice of quartz or along a magnetic field, is a wider generalization of more recent date; but one of the reality of which I hope to convince you before the warning finger of the clock puts a period to my discourse.

In order the better to enable this audience to comprehend the ultimate significance of this discovery, I must claim the indulgence of those amongst them who are already familiar with the subject of the polarization of light, whilst I go back to the most simple elementary matters. Having illustrated the fundamental facts about the plane of polarization of light and its twisting, I shall then go on to methods of precisely measuring the amount of optical torsion produced by the various substances under various conditions. And after dealing with the magnetic as well as the crystalline and molecular methods of producing optical torsion in the case of light that has been previously polarized into a given plane, I shall be in a position to speak of the nature of the torque,[1] or twisting force, which in the several cases produces the torsion; and shall finally endeavour to indicate the scope of the researches by which it is now definitely ascertained that the very same optical forces which are capable of impressing a rotation upon light which has been artificially polarized into a definite plane are also capable of impressing a rotation upon natural, non-polarized light.

At the outset, to elucidate to any who may not comprehend the meaning of the term polarization as applied to wave-motion, I will show a simple apparatus, constructed from my designs by Mr. Groves. In this there are two sets of movable beads, fixed upon stems which pass into a box containing a piece of mechanism actuated by means of a handle. These beads, when I turn the handle, oscillate to and fro in definite directions, and, by their successive motions, give rise to progressive waves. One set of beads, tinted red, executes movements in a plane inclined 45° to the right, another set, silvered, simultaneously executes movements at 45° to the left. There are therefore here two waves, the planes of polarization of their movements being at right angles to one another. Their velocity of march is equal; but in this model, as a matter of fact, their phases differ by one-quarter—that is to say, each successive wave of the one set is always a quarter of a wave-length behind the corresponding wave of the other set. [Model exhibited.]

Now, in the case of waves of natural light from all ordinary sources—sun, stars, candles, gas-flames, or electric light—the waves emitted are not found to be polarized. That is to say, their motions are not executed in any particular plane, nor even in any particular path of any kind; they appear to be absolutely heterogeneous at least so far as this, that no vibration of the millions of millions emitted in a second of time is followed by more (on the average) than about 50,000 vibrations of a similar sort, executed along a similar path—the plane of the polarization, if any, changing after the lapse of such an incredibly short time that for most purposes the vibrations in different directions are as inextricably mixed as if they had all been simultaneously jumbled up. Since, then, natural light is non-polarized or miscellaneous, the production of polarized light must be brought about by the employment of polarizing apparatus or agents which will so operate on or affect the mixed waves as to bring their vibrations into one direction—or, what amounts to the same thing, transmit the light whilst destroying or absorbing those parts of the vibrations which are executed *across* the desired line of vibration. So we have *polarizers* consisting of tourmaline slices; oblique bundles of thin glass plates; black-glass reflectors; and Nicol prisms cut from calc-spar. About the two latter I may be permitted a passing word presently. These objects polarize, *i.e.* turn into one plane, the vibrations of light falling upon them. A rough mechanical illustration may here be permitted me. A long india-rubber cord is passed through the open ends of a box provided with vertical partitions. Fig. 1 shows the arrangement. These partitions confine the motion of the cord, and effectually polarize the vibrations which I now impart to the cord by shaking the end of it to and fro. If the partitions are vertical, the box polarizes, into vertical vibrations only, the miscellaneous vibrations which are sent to it. If rotated until its partitions are horizontal, it polarizes the vibrations into a horizontal position.

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[1] A Discourse delivered at the Royal Institution, May 17, 1889, by Prof. Silvanus P. Thompson.

[1] The convenient term *torque* was first proposed by Prof. James Thomson, of Glasgow, for the older and more cumbrous phrase "moment of couple," or "angular force." Its general acceptance by engineers justifies the extension of the term to optics. As a mechanical torque is that which produces or tends to produce mechanical torsion, so optical torque may be defined as that which produces or tends to produce optical torsion.

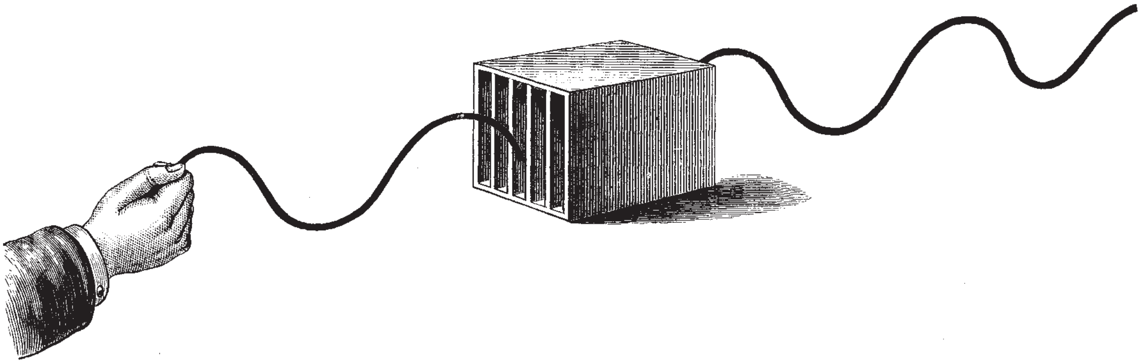

Fig. 1.—Box with partitions to illustrate polarization of vibrations.

Let us now turn to the optical analogue of this experiment. The large Nicol prism which I introduce into the field of the electric-light lantern, polarizes the light, so that the vibrations are executed simply in an up-and-down direction. Your eye will not detect this, the motions being millions of times too rapid. To detect the direction, an analyzer is necessary. For this purpose a second apparatus of the same sort is used, for then, by crossing the positions of the two, the whole of the light is cut off; the second Nicol prism, if set so as to transmit only horizontal vibrations, cutting off the vertical vibrations that are sent through the first prism. So, whilst the first prism serves as a polarizer, the second serves as an analyzer to detect by cutting them off when turned to the proper position, the direction of the polarization which had been previously impressed by the first prism.

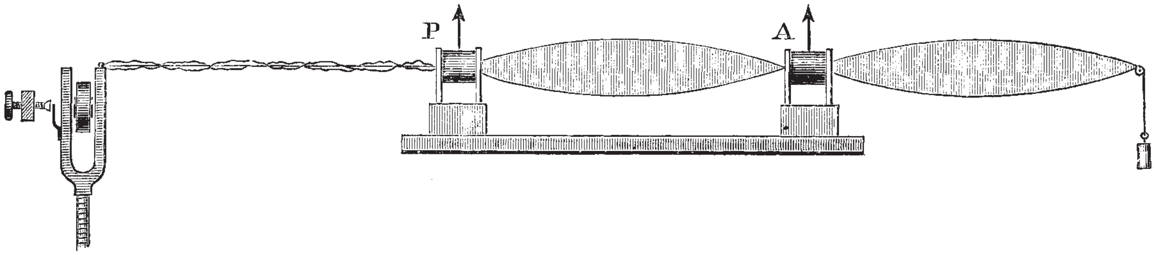

Fig. 2.—Acoustic model illustrating polarization of vibrations. P, the polarizer; A, the analyzer.

Here I may illustrate the action of the analyzer for determining the plane of polarization of the vibrations, by the extinction which it produces when turned to the crossed position. For this purpose I have refined upon the box with partitions, using instead parallel plates of glass mounted in wooden cylinders, whilst for the cord swung by hand I am using Prof. Schwedoff's device, and am producing the vibrations in this silken cord by means of an electrically-driven tuning-fork (Fig. 2). At the first nodal point of the stretched cord a pair of parallel glass plates acts as a polarizer, the cord from that point vibrating in the *plane thus imposed upon it. I can alter this plane at will by* rotating the polarizer. This polarizer, P, consisting of a pair of glass plates, is mounted in a cylindrical mount, and is provided with an arrow to indicate their direction. If now at any subsequent node I introduce a second such device, it will act as an analyzer, A. This excellent suggestion is due to M. Macé de Lepinay. In Fig. 2 the polarizer and analyzer are parallel. *You see (Fig. 3) how the vibration is extinguished when the* positions of analyzer and polarizer are crossed. Half a degree of error in the position of the analyzer produces something less than perfect extinction of the vibrations. Hence it is possible, by this analyzer, to determine the plane of the vibrations to the accuracy

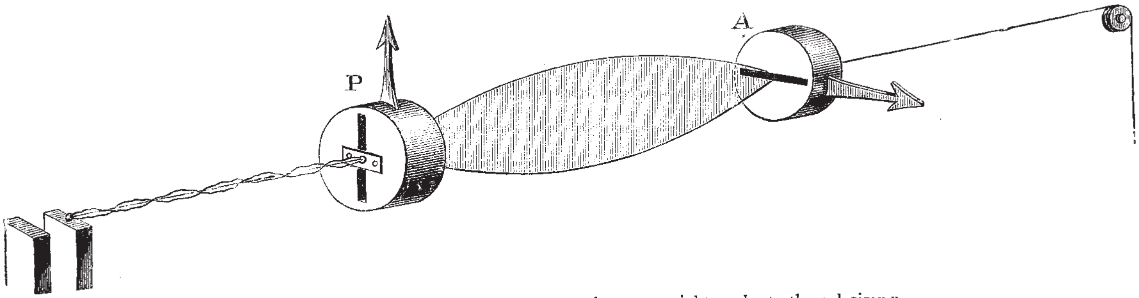

Fig. 3.—Vibrations cut off by turning the analyzer A at right angles to the polarizer P.

of half a degree. I should say that the whole of this model has been constructed by my assistant, Mr. Eustace Thomas.

Now let me show you the optical effect which corresponds to this. Placing a second Nicol prism as analyzer in the path of the polarized waves, I turn it to the position where it cuts off the polarized light. The "*dark field*" so produced by the crossed Nicol prisms corresponds to the motionless cord beyond the crossed analyzer of the acoustic apparatus.

Returning for a moment to two well-known forms of polarizing apparatus, viz. the black glass reflector and the Nicol prism, I may be permitted to refer to some recent attempts to improve upon these devices.

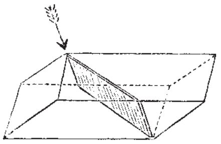

Fig. 4.—Nicol prism: original form.

The Nicol prism, as is well known, consists of a rhomb of Iceland spar cut into two pieces, which are reunited by a film of Canada balsam. As originally devised, it had oblique end faces (Fig. 4), and a comparatively narrow angle (19°) of aperture. These may be noticed in the small example which I here exhibit, which is an original constructed by William Nicol himself. It also has the disadvantage of giving a field in which the directions of the planes of polarization are not strictly parallel to one another throughout its whole extent. Consequently there is never complete extinction of light all over the field at one time. Hartnack and others have attempted to remedy this by giving the prism a different form and using other materials than Canada balsam. I have from time to time made many attempts to improve upon the original construction. First, I have made the end faces principal planes of section (Fig. 5); secondly, I have made the axis of vision cross the crystallographic axis at right angles, so getting a flatter field, a shorter length, a wider angle, and less loss of light by reflection. Mr. Ahrens, the prism-cutter, on whose able assistance I have relied during the last six or seven years in cutting these prisms, has aided me with his ingenuity in devising a method of cutting up the spar so as to give these advantages with a minimum waste of material. He has further devised a method of putting a polarizing prism together in three instead of two pieces—illustrated in the diagram (Fig. 6)—which gives a still wider angle. The prism which I shall use as analyzer in the next experiments is one of these forms.

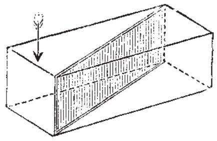

Fig. 5.—S. P. Thompson's modification of the Nicol prism.

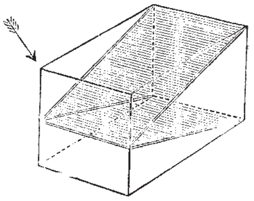

Fig. 6.—Ahrens's triple prism.

Unfortunately at present there is a spar-famine, pieces of Iceland spar of a size and purity suitable for the making of large polarizers such as that I employ being not now procurable at any price. To avoid the excessive cost of large Nicols I have lately got Mr. Ahrens to construct for me a large reflection-polarizer, on the plane of Delezenne, but modified by Mr. Ahrens in detail. In this prism the light is first turned to the proper polarizing angle by a large total-reflection prism of glass, and then reflected back, parallel to its original path, by impinging upon a mirror of black glass covered by a single sheet of the thinnest patent plate-glass to increase the intensity of the light. This form of polarizer, depicted in Fig. 7, is quite equal for projection purposes to a Nicol prism of equal aperture, and is much less costly. This one has 2½ inches clear aperture.

Having so far reviewed the apparatus for polarizing and analyzing, I will return to the apparatus set with its prisms crossed, so that the analyzer completely extinguishes the polarized light emitted from the polarizer.

If in the space between polarizer and analyzer anything be introduced which can either resolve obliquely the polarized vibrations or twist them bodily round, then there will not be complete extinction; the amount of light passing the analyzer depending in the one case on the obliquity of the resolution, in the other upon the degree to which the vibrations are twisted or rotated upon themselves.

The effect of oblique resolution I may illustrate by introducing a slice of tourmaline between the crossed Nicols, and rotating it till it stands at 45°; or, in the acoustic model, by introducing an oblique pair of guide-pins.

The other case—namely, that of producing a bodily twist of the vibrations, rotating the plane of polarization around the path of the wave—is not so easily illustrated by the model. But it is optically perfectly simple: all that is requisite is to introduce between the crossed Nicols a thin slice of that crystal—namely, quartz—in which this effect of rotating the plane of polarization was first observed.

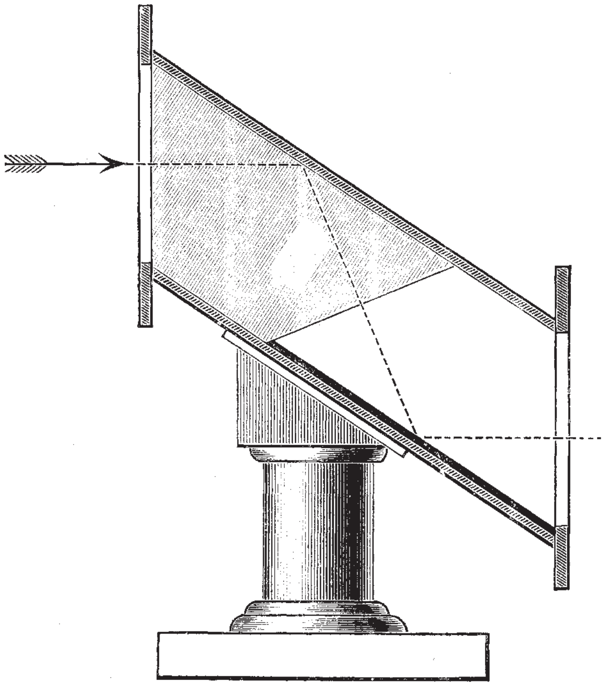

Fig. 7.—Ahrens's reflecting polarizer.

I take a clear plate of quartz, just 1 millimetre in thickness, and interpose it between the crossed Nicol prisms. You will note how the introduction of this plate of quartz brings *some* light into view.

Suppose we now turn the analyzer to try and obtain extinction: we get tinting. If we put in a coloured glass so as to work with one kind of light only, we shall get extinction at a particular angle. The table of data to which I invite your

*Optical Torsion produced by Plate of Quartz.*

| | 1 millimetre. | 3·75 millimetres. |
|---|---|---|
| | ° | ° |
| Red | 19 | 71·2 |
| Orange | 21·5 | 80·6 |
| Yellow | 24 | 90 |
| Green | 29 | 108·7 |
| Peacock | 31 | 116·2 |
| Blue | 35·5 | 133·1 |
| Violet | 42·8 | 161 |

attention states this amount for the different colours. If we use a piece of quartz so thick that it rotates any particular tint just 90°, that tint will be cut off by the crossed analyzer, and all others will—in greater or less proportion—be transmitted, so that the resulting tint will be complementary to that cut off. For example, a slice just so thick as to twist yellow waves round 90° must be 3·75 millimetres thick. (I may remark, for the benefit of those who think it easier to express this exact thickness in fractions of a British inch, that the quartz which rotates yellow light 90° must have a thickness equal to one-eighth, plus three-sixteenths of an eighth, plus one sixty-fourth of an eighth of an inch.) When such a quartz is placed between the crossed Nicols, the light shown is yellow; but if placed between parallel Nicols (*i.e.* in the bright field), it shows a rich purplish-violet colour, the complementary of the yellow. This particular tint Biot found to be excessively sensitive, the smallest inaccuracy in adjustment between the prisms at once producing a change, the colour appearing too red or too blue, according to the direction in which the analyzer has been turned out of exact adjustment. This tint is accordingly known as the "transition tint" or "sensitive tint," its accurate definition being due to the fact that the human eye is more sensitive to the presence or absence of the complementary yellow than to any other tint in the whole spectrum. If we take, however, a quartz plate twice as thick as this—namely, 7½ millimetres thick—this will give the yellow light a torsion of 180°. Hence this gives the purple transition tint in the dark field, and is yellow in the bright field. A quartz plate 11¼ millimetres thick gives again a transition tint in the bright field. I shall recur presently to the question of the transition tints of the several orders.

One of the familiar facts in this subject is that there are two kinds of quartz crystals, optically alike in every other respect, differing only in this, that one kind produces a right-handed twist, the other kind a left-handed twist. All the pieces of quartz I have so far employed are right-handed specimens. I now introduce two small slices of crystal, each 3¾ millimetres thick, giving the yellow tint when the Nicols are exactly crossed, but you will notice that when we are using the right-handed crystal, the tint grows reddish as the analyzer is turned towards the left, and greenish when the analyzer is turned towards the right; whereas, when I substitute the left-handed slice, the tint grows greenish as the analyzer is turned toward the left, and reddish when it is turned toward the right. If the analyzer is turned through an exact right-angle, we get an extinction of the yellow light, the remaining blue and red rays combining to give us the purple transition tint.

You will have noticed that the way in which we have (approximately) measured the angle of rotation has been first to set the analyzer to extinction, then to introduce the substance which has the property of rotating the beam, then to turn the analyzer again to extinction, and read off its angle. For, of course, the angle through which the analyzer is turned measures the angle through which the plane of polarization has been turned.

It is possible, however, to show in the lantern something like a more obvious rotation of the light by introducing between the Nicols a crystal star, built up of radial pieces of mica, twenty-four in number (Fig. 8). You see in the bright field a white cross with black sectors at 45°. Or, in the dark field we have a black cross with vertical and horizontal arms, the sectors next to those that are black seeming dusky. If now I put in a quartz plate between the star and the analyzer, you see the cross shift round, and it shows colours, because the blue rays are twisted round more than the green, the green than the yellow, the yellow than the red. Repeating the experiment with the 3·75 millimetre quartz which turns yellow waves round just 90°, we get this gorgeous radiation of colours, and our black cross is turned into a yellow one. With the 7·5 millimetre quartz, the black cross is replaced by one of "transition" tint.

The black crosses seen in certain sections of natural crystals, sphæroliths, sections of stalactites, crystallizations of salicine and of Epsom salts, may also be used instead of the 24-rayed star of mica. But best of all I find to be the beautiful black cross which is seen by polarized light in the prepared crystalline lens taken from the eye of a fish. You notice how, when the fish lens is projected and the quartz introduced, the cross turns round.

This is, however, a rough-and-ready way of displaying the rotation, and it is of vast practical importance that precise methods of measuring the angle of rotation should be available—of vast importance, because in several large industries this optical method is applied as a species of handy analysis. I have named a solution of sugar as being an "active" substance. In the industry of sugar-refining, as in that of brewing, the strength of sugar in the liquids is directly measured by measuring its optical effect. Consequently there has been developed a special instrument, the *polarimeter*, for this express purpose.

I have here examples of several practical forms of polarimeters; there are diagrams of several more upon the walls.

The problem of finding the best polarimeter naturally leads to the inquiry what special means are there for making the observation of the angle more precise than by merely observing the extinction of the light, its restoration when the active substance is interposed and the subsequent renewal of extinction when the analyzing prism is turned.

Biot considered that much greater accuracy could be attained by watching for the restoration of the sensitive tint than by watching for the mere restoration of extinction of the light. Accordingly we will use the plate of quartz 7·5 millimetres thick, giving the purple tint, to enable us to measure the rotation produced by the tube of sugar solution which is now inserted in the beam of polarized light. You notice how the tint has changed. But I have only to turn the analyzer to an amount equal to that to which the light has been twisted by the sugar, and again I obtain the sensitive transition tint.

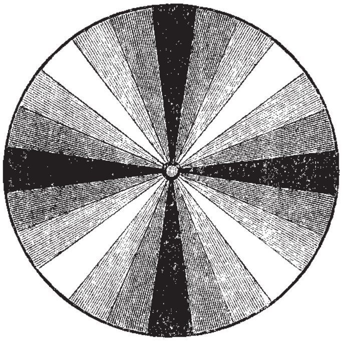

FIG. 8.—Mica disk of twenty-four rays, showing black cross in the dark field.

The eye is not always, however, alive to minute changes of colour in a single coloured patch; it much more readily distinguishes a minute difference between two tints when both are present at once. Hence Soleil devised the well-known biquartz arrangement, consisting of two pieces of crystal, equal in thickness but possessing opposite rotations. You will notice how the slightest inaccuracy in placing the analyzer causes the two halves of the field to differ in tint. This is especially marked when the tint chosen is the transition purple.

(*To be continued.*)

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## *THE PLANET URANUS.*

THAT anomalous section of the solar system, Uranus and its satellites, offers yet a wide field of investigation to astronomical specialists of all kinds. Its figure, its rotation, satellites, and physical constitution altogether, are moot points, which should be more or less settled with the increased optical power now at our disposal.

The circumstances attendant upon the discovery of Uranus in 1781 (Phil. Trans., 1781, p. 492) are matters of common knowledge. The planetary nature of the supposed comet seems to have been first suspected by Maskelyne, and it was this suggestion that induced Lexell to calculate for it a circular orbit in 1781 (Grant's "History of Physical Astronomy," p. 274). The elliptic elements of the planet were first calculated by Laplace in 1782 (*Mém. Acad. des Sciences*, Paris, January 1783).

The first measures of the Uranian diameter were singularly incongruous. Herschel found it in March 1781 to be 2″·53; whilst in the following month he measured it as 4″·52 and 5″·2, (Phil. Trans., 1781, p. 494). A like discordance occurred in the results obtained by other astronomers. Maskelyne fixed the magnitude of the apparent diameter as 3″, whilst Mayer, of